ATLAS Pixel Module Assembly

ATLAS Project Document No:	*ABS item number*	*Created:* 11 Nov. 2002	*Page:* **1** of *31*
ATL-IP-AN-0003		*Modified*: **16 Oct. 2003**	*Rev. No.:* **3**

ATLAS Pixel Module Assembly

Abstract

This document describes the ATLAS pixel module and the assembly process. It has been prepared for the Module Assembly Final Design Review and updated for the Production Readiness Review.

Prepared by: R. Boyd, G. Darbo, A. Eyring, M. Garcia-Sciveres, C. Gemme, P. Netchaeva, W. Ockenfels, O. Runolfsson, L. Rossi, E. Vigeolais, N. Wermes	*Checked by:*	*Approved by:*

Distribution List

History of Changes			
Rev. No.	*Date*	*Pages*	*Description of changes*
1	4/12/02	All	General comments and late contributions added
2	12/2/03	-	Impedance of type 0 cables is now fixed at 75 ohms.
3	16/10/03	All	Update for PRR

Table of Contents

1   INTRODUCTION

The basic active unit of the pixel detector is the bare module (see ATL-IP-AN-0002). However, a bare module, as the name suggests, lacks the necessary connectivity and services to make it usable by itself. The purpose of module assembly is to integrate the bare module with other components into a self contained unit, the module proper, which is as much as possible a stand-alone device, that can be handled without special precautions, easily plugged into a test data acquisition setup, and used to detect particles from radioactive sources, test beams, etc. A standard format, stand-alone functional module is crucial to the development work necessary to learn how to build and operate a large pixel detector.

While the stand-alone module is a critical element, the ultimate purpose of modules is to be integrated into a full scale detector. Thus the module is designed such that after stand-alone use it can be easily reconfigured and integrated into a multi-module assembly. Such assemblies are "staves" in the case of the ATLAS barrel and "sectors" in the case of the disks. The mechanical structures that hold modules together in a stave or sector are referred to as local supports. The process of loading modules onto local supports is included in the scope of this document.
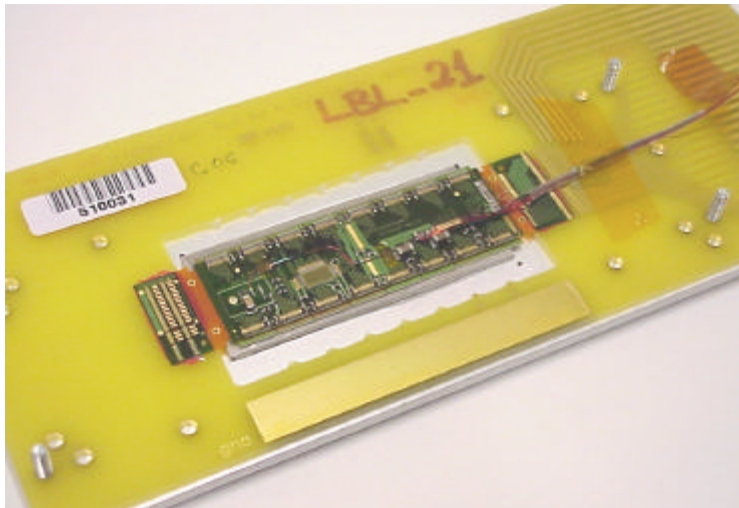

Figure 1: A fully assembled module in its PCB frame.

At the centre of the module assembly sequence and stand-alone module concept is a printed circuit board referred to as the PCB frame. The various components which make up the module are integrated by adding them to the frame assembly, which serves as a temporary support throughout the process, and defines the stand-alone module geometry. The flex hybrid is fabricated with sacrificial end pieces that are permanently glued to the frame soon after manufacture. All assembly operations then proceed on the PCB frame, starting with loading of surface mount components and ending with flex hybrid to bare module wire bonding. In order to separate the module from the frame, prior to loading on a local support, the sacrificial ends of the flex hybrid are cut and remain behind still attached to the discarded frame. A photo of a fully assembled module in its frame is shown in Figure 1.

2   MODULE COMPONENTS

The components that are combined to form a module are listed below and illustrated in Figure 2 and Figure 3.

1. Bare module (sensor bump-bonded to FE chips)
2. Flex hybrid

3. MCC chip
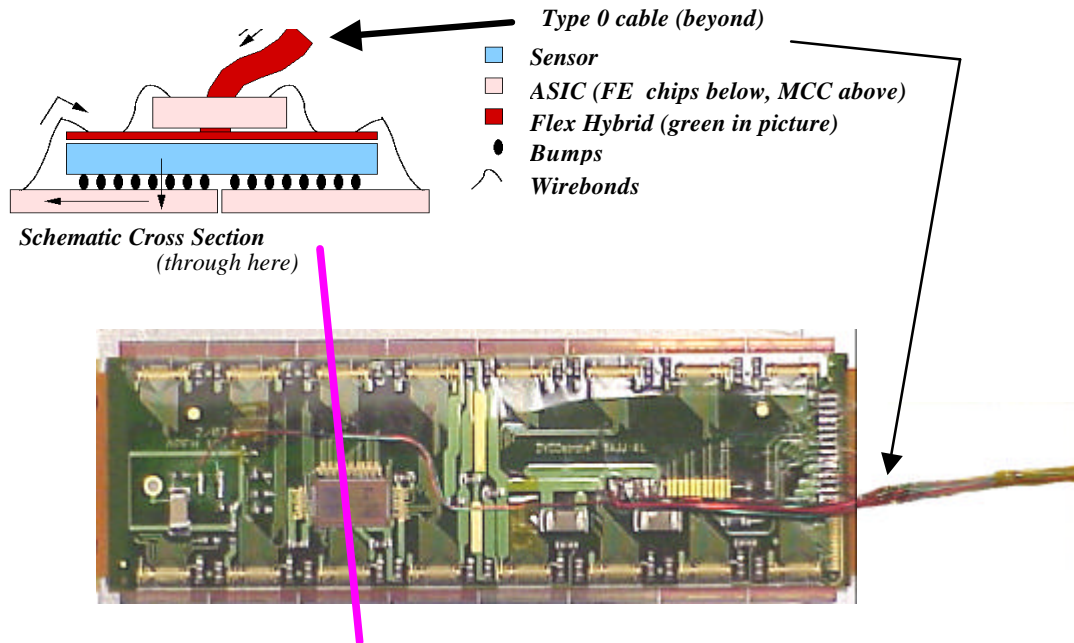4. Pigtail (barrel) or type 0 cable (disk)

Figure 2: Components of a Pixel Module (module shown in photo has a disk type 0 cable).
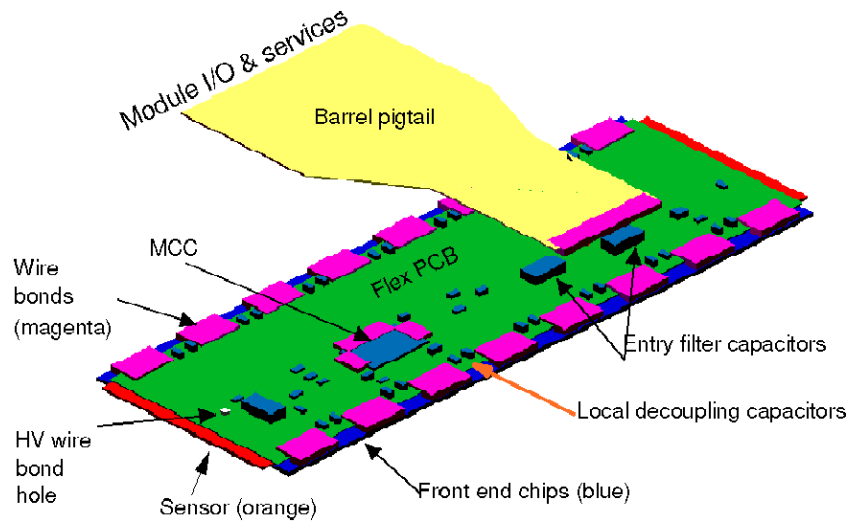

Figure 3: Conceptual 3-D view of a module (shown with barrel pigtail).

The bare module is by far the most complex and valuable component and it described in detail in a separate document (ATL-IP-AN-0002). While the flex hybrid is described in detail in fabrication documents, a description is also included here because of its central role in module assembly. The modules to be used in the barrel have an additional flexible printed circuit (pigtail) attached to the flex hybrid. All barrel modules have the same pigtail. The pigtail holds a connector that mates to an electrical cable (one per module) which supplies all power and communication (known as type 0 cable). In contrast, disk modules have their type 0 cable permanently attached, without an intervening connector. There are

two lengths of disk type 0 cable (one length for disks 1 and 3, another for disk 2), and consequently two types of disk module. All disk and barrel modules have identical bare modules and flex hybrids.

2.1 The Flex Hybrid

2.1.1 *Architecture*

Complete schematics, fabrication drawings, bills of materials and other drawings of the flex hybrid prototypes are available from: http://www.nhn.ou.edu/~boyd/atlas_html/base.html. The flex hybrid provides the routing between the 16 front end (FE) chips and the MCC on a module. The Flex Hybrid block diagram is shown in Figure 4. All the connections that are active during data taking use LVDS signals to reduce EMI (Electro-Magnetic Interference) and balance current flows. Control and other low speed signals are CMOS logic level. Modules are completely independent from each other for data transfer and communicate with the off detector electronics via two or three serial links plus a clock. One or two links (depending on required rate) are for transmission of event data, and one for reception of timing and control signals. The interconnections between the MCC and the 16 FE chips in a module follow a star topology for data transfer out of the FE chips, which uses unidirectional serial links (Figure 5). The timing and control signals utilize an "H" bus topology (Figure 1). The input LVDS signals are singly terminated by 75 Ω resistors (dictated by the type 0 cable impedance), the outputs are not on the module
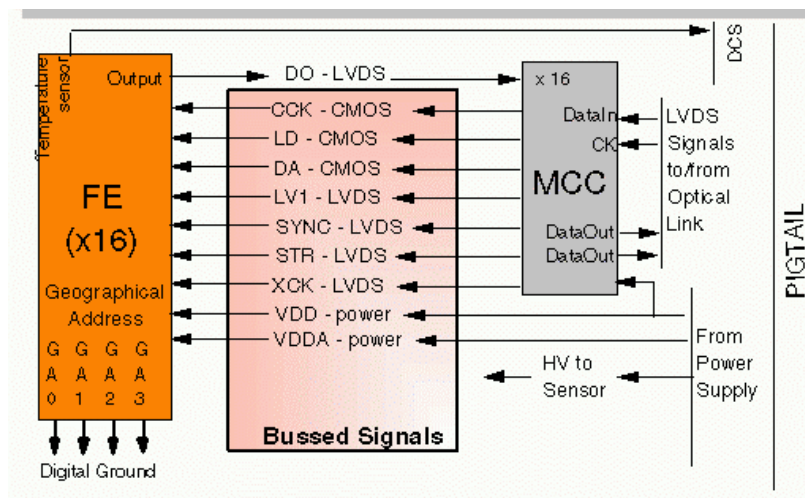

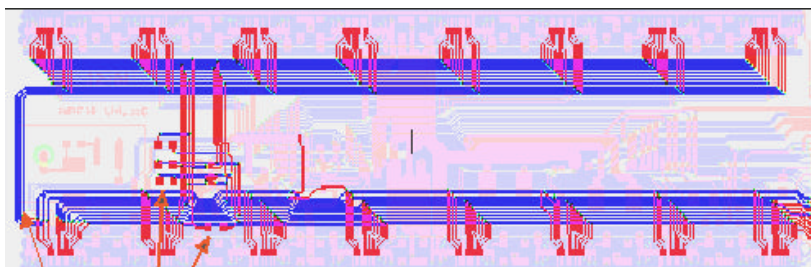Figure 4: The Pixel flex hybrid block diagram.

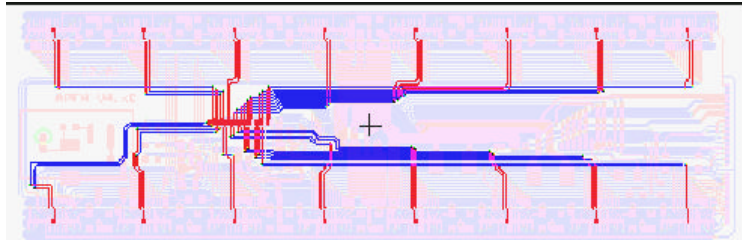Figure 5: Star topology of the FE outputs routed to the MCC.

Figure 6: H-bus topology control signal routing on the flex hybrid.

The power is filtered by 1206 size, 10 µF ceramic, X5R characteristic, 10 WVDC capacitors at the entry points near the pigtail bond pads. Power is bussed starting between FE-3 and FE-4 on one edge and between FE-11 and FE-12 on the other (Figure 7) in order to balance the voltage drops at the FE's in the corners. There is also a 0.1 µF ceramic X5R characteristic 10 WVDC Local Decoupling Capacitor (LDC) for each supply between each pair of FE's. The digital supply and return, VDD and DGnd, are routed nearest to the FE bond pads in order to minimize ringing due to inductance. The power trace widths are maximized in order to meet the required round trip voltage drop of 0.1 Vdc at the maximum expected current (after radiation damage to the electronics). Although the technology is available, It is not possible to add power and ground planes without increasing the material proportionately. Results with FE-I modules indicate that there is no important difference compared to single chip modules operated with "ideal" power routing using layers in a PCB for power distributions instead of traces.
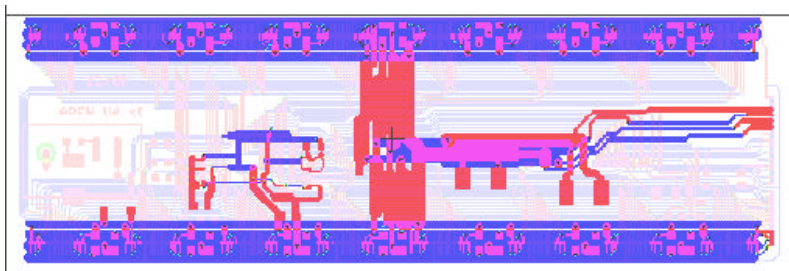

Figure 7: Power routing on the flex hybrid (individual traces not everywhere visible in this picture).

2.1.2   *Flex Hybrid Construction*

The flex hybrids are based on Flexible Circuit Board technology (FCB). For the ATLAS Pixel modules, the FCB is a 50µm thick polyimide substrate with patterned copper traces on both sides. Thinner material (25µm) was done in prototypes, but it resulted in significant bow as well as higher order deformations (ripples) that hindered module assembly. Ripple is completely absent from production flex hybrids. Metal plated through-hole vias connect the top and bottom traces. Polyimide materials were selected for the substrate because it has low radiation cross section, good thermal dimensional stability, it resists shrinkage, is radiation tolerant and is generally preferred by manufacturers. Together with its high dielectric strength of 300V/µm and radiation resistance to 100Gy, it offers a high degree of functional reliability. The conductor is built up by first sputtering a seed metal such as Ti or Cr before electro-plating with Cu (adhesiveless copper). The final Cu thickness is 17 - 20µm for both metal traces and vias. To allow for both soldering and aluminum wedge bonding, a 2µm layer of electroless Ni is plated over the Cu and then a 0.1µm to 0.2µm layer of electroless Au is added. The Ni and Au layers may be applied to all the metal traces or just the solder pads and wire bond pads, depending on a particular vendor's process.

Cover layers are used on both sides to stabilize the traces and make the flex circuit more robust. On the bottom, this cover layer must also withstand the high bias voltage required for the sensors after type inversion and with increasing radiation damage. The specified value for the maximum bias voltage is

600 V. Currently, we test the bottom cover layer to 800 V after components have been loaded onto the flex hybrid, but before attaching the MCC. The specification for manufacturing is that the cover layer must have at least a one thousand volt hold off strength. There cover layers are made with commercial solder mask materials (with proprietary chemistry, call them "green solder mask") that have been seen to withstand high voltage and irradiation. It is applied as a liquid photo-imageable product in at least two layers to avoid pinholes. The typical thickness of the bottom layer is 90μm. A CTE mismatch between the green solder mask and the polyimide substrate results ins a slight downward bow of the hybrid edges relative to middle. This bow direction does not hinder module assembly.

2.1.3   Design Features

Both the disk and barrel modules use the same wire bondable pads for connection of the pigtail or type o cable, respectively. In order to make room for this pigtail connection and to provide the 700 V isolation specified, the sensor high voltage connections are made at two wire bondable pads at the opposite end of the flex hybrid from the pigtail connections (Figure 8). The sensor bias wire bond is made through a 1 mm hole exposing a pad on the sensor. As shown in Figure E, HV hole and the other high voltage traces and components are somewhat isolated from the rest of the flex hybrid by a 100μm wide "guard ring" trace in the top metal (all high voltage routing is done on top) connected to Analogue Ground and the detector bias return.
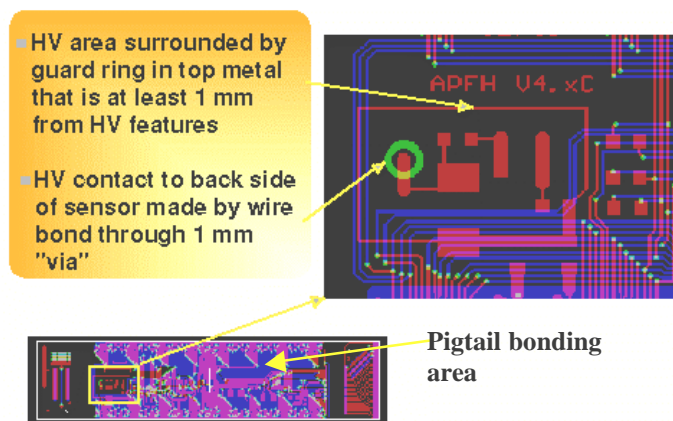

Figure 8: Location of sensor bias input and detail.

The guard ring is a minimum 1 mm from any high voltage carrying trace or component. Although less than the distance recommended by some sources, one should keep in mind that the modules will operate in a dry nitrogen atmosphere and that the terminals of the high voltage filter capacitor are less than 1 mm apart. The layout of the high voltage components is such that it is within an area of maximum headroom with respect to the mechanical envelope. This allows space for a high voltage potting compound to be applied to prevent arcing to other flex circuit components and to adjacent stave supports in the barrel.

The delivered length of the flex circuit is 87 mm x 19.6 mm, approximately 23 mm longer than the final specified length. The excess length is primarily utilized for mounting the flex circuit to a frame PCB. The extra room at one end is used for test structures. These include via chains and three different widths of traces for measuring the resistances of these features. Practice wire bond pads are also included, to be used in various wire bond tests. The other sacrificial end is used to route power and signals between flex hybrid and frame PCB. In addition, power and signals are routed at the same end from one corner of the busses on the flex hybrid to provide monitoring capability during development and debugging. Connections to the frame PCB are made with wire bonds.

2.2   Barrel Pigtail and Type 0 cables

The Kapton flex circuit called Barrel Module Pigtail provides the connection between the type0 cables and the Flex-Hybrid. It routes the signal lines (data, slow control and sensor bias) and the low voltage power lines. By bending around the side of the module it brings the electrical services of a module to the back of the stave local support. At the module end of the pigtail, the signal and power lines terminate in wire bond pads and at the other side they end in a 36 pin ELCO connector footprint (see Figure 9).
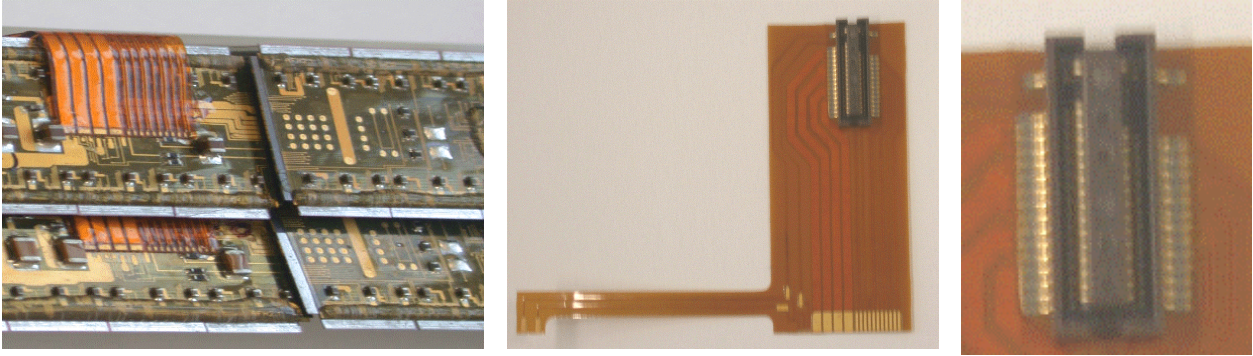

Figure 9: Close up of bi-stave with barrel pigtails bent around modules (left), Barrel pigtail flex circuit (center), close up of ELCO connector (right).

The pigtail also carries the sensor bias high voltage via the connector to the extension part (leg), on which the wire bond pad for the bias contact is found at its end (center photo Figure 9). The HV lines have a larger pitch than the power and signal lines to provide sufficient electrical insulation. Also, inside the ELCO connector six contact pins have been removed for this purpose. The electrical insulation was tested to stand 1.6 kV.

In order to stay within the 0.5A per contact specification of the ELCO connector, three pins are used for each of the 4 power and ground lines. HV and sense lines, data and slow control use one pin only, totaling 30 pins altogether.

The pigtail flex Kapton is a Du Pont Paralux LF Copper-Clad laminate with 50µm Kapton, 18µm annealed Cu and a 50µm Paralux LF cover layer. A stiffener made of FR4 is added under the connector.
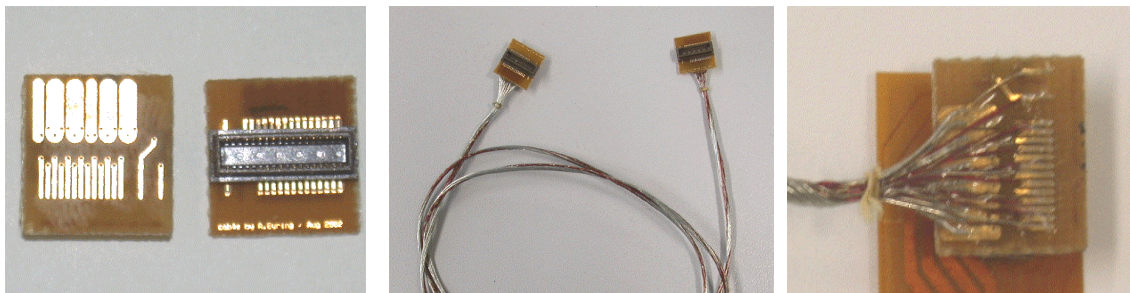
Figure 10: ELCO connector (type0 end) on FR4 board showing the micro welding side and the soldering side (left). Type0 cable with connectors on both ends (center). Type0 cable connected to pigtail ELCO connector (right).

A barrel Type 0 cable and termination details are shown in Figure 10. The Type0 micro cables connect each module pigtail to a matching ELCO connector at Patch Panel 0 (PP0) at the end of the pixel detector. The power lines are made of 300µm pure Al wires with 3µm polyurethane insulation. The signal

lines are 100μm Al 99.5% with 30μm polyurethane insulation for low voltage and 25μm insulation for HV. The data lines are twisted for proper data transmission and have a characteristic impedance of 75 Ohms.

The type0 cable must be fabricated in 16 different lengths (720 mm to 1320 mm in steps of 40 mm) to supply the 13 modules at individual positions of the stave. To keep the power line voltage drop of each cable length around 550 mV, the power lines are made from one, two or three wires for each voltage.

Two small FR4 boards (11mm x 12mm) at each end of the type0 cable with a soldered ELCO connector terminate the cable. The different Al wires are micro welded on the back side. To protect the micro-welded cable on the board, and to insulate and strain relieve them, potting is done on the entire board area. For corrosion reasons, a special UV curing potting epoxy with very low contamination of chloride, sodium, fluorine and potassium ions (below 10 ppm) has been used.

All cables are foreseen to be tested using an automated cable tester which has been developed for this cable. It tests for shorts, missing lines and voltage drop. HV tests and tests of proper data transfer will be done separately.

2.3   Disk Type 0 Cables

For disk modules the Type 0 cables are permanently attached (soldered) to the flex hybrid. The disk geometry and assembly process allows for this, eliminating the need for a pigtail connector and for wire bonded module power and signal connections. A barrel type pigtail with connector would also add complexity, as there is not single pigtail shape that can work for all disk modules and there is no natural location for the connector. Because the type 0 cable comes off straight along the long axis of the module it does not interfere with module assembly and wire bonding operations.

The disk type 0 cable uses different conductors than the barrel, primarily because of the need to solder the wires to the flex hybrid (micro welding does not work on a flex substrate). The power leads are made of 400μm diameter copper clad aluminium, which is solderable like copper, but contains only 10% copper by volume. The signal wires use pure copper 62μm diameter wire twisted pair. The material contribution from such fine wire is small compared to the power leads. All wires are insulated with polyurethane (magnet wire insulation). The bias voltage wires are also solid copper, but the insulation is 25μm thick polyimide. The additional radiation thickness in the wires compared to pure aluminium as in the barrel is offset by the lack of a connector between pigtail and type 0 cable, so in the end both disk and barrel cable implementations contribute the same average material per unit length. At the end of the disk type 0 cable is an FR4 board with a soldered 36 pin connector, the same as on the barrel type 0 cables.

3   ASSEMBLY STEPS

The various operations in building a module are listed here in approximately the order in which they are performed. There are cases where the order is not fully decided or may be different for disk and barrel modules. A detailed description of each step is documented in the Assembly Breakdown Structure (ABS). The steps are:

   A. Attach bare flex hybrid to frame
   B. Load surface mount components on flex hybrid
   C. Attach disk type 0 cable OR wire bond and encapsulate test connections
   D. Test high voltage isolation of flex hybrid
   E. Attach MCC chip to hybrid and wire bond.
   F. For barrel only, attach pigtail to hybrid and wire bond.

G. Detailed electrical test of flex hybrid with MCC, including test of wire bond sites for each future FE chip.

H. Glue bare module under flex hybrid and wire bond FE chips.

I. Partly encapsulate power wire bonds (to prevent vibration in magnetic field).

J. Test and burn-in full module.

K. Remove selected full modules from frame and load on local support
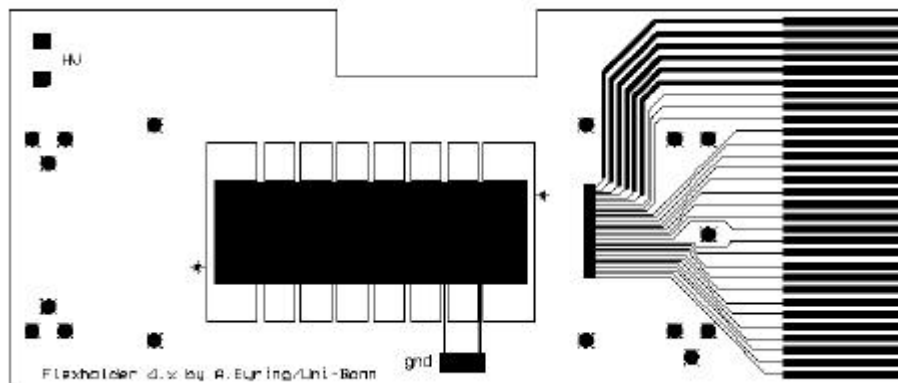
4   PCB FRAME

Figure 11: Frame printed circuit board

The frame PCB is a 2-sided copper on FR4 board 78mm x 187mm by 1.5mm thick (see drawing Figure 11). It has a central "knock-out" section (solid back in the figure) that forms a backing for the flex hybrid when it is first laminated onto the frame. Two reference holes on the frame PCB match up to similar holes on the flex hybrid ends used to register the flex for lamination. During surface mount component loading onto the flex hybrid as well as MCC chip loading and wire bonding, the frame knock-out provides a rigid support. The knock out region also provides a metal ground plane underneath the flex hybrid used during high voltage isolation testing of the bottom cover layer. It is important to note that even though the flex hybrid is made on a "flexible" polyimide substrate, the metalization is not designed to withstand repeated bending. By laminating the flex hybrid on the frame and performing all assembly and testing operations on the frame it is guaranteed that the flex hybrid is never bent.

On one end of the frame PCB is a row of wire bonding pads that match the flex hybrid test connections. There are only used on barrel modules, during high voltage testing of the flex hybrid by itself and electrical testing of the flex hybrid with MCC. The test connections are brought to the edge of the frame PCB to a 2.54mm pitch card edge connector filed. This is used for making reliable repeated connections to multiple test setups, while avoiding the expense of an actual connector on the frame.

When times comes to glue the flex hybrid to a bare module, the frame knock-out is removed by cutting small tabs. The bare module then occupies the former location of the knockout, and the fully assembled module is mechanically suspended in the frame via the two sacrificial ends on the flex hybrid. This permits safe handling without having to touch the module.

There are 10 locator holes of various sizes on the frame designed to fit various assembly fixtures. 4 of these holes are also used to locate protective "shipping" covers on the frame- a plain aluminium back and static-dissipative clear plastic front with a milled cavity to accommodate the flex hybrid components. These covers are kept on the frame except for assembly operations, and permit very reliable and safe handling of hybrids and even fully assembled modules. In the case of a full module a shim is glued to the aluminium back to make up the thickness difference between the 1.5mm frame and the 0.5mm bare

module. Proximity contact between the bare module and the shim provides adequate cooling for module operation.

Finally, the frame provides a convenient location for a bar code identifier used to track flex hybrids first and modules later. This is described in ATL-IP-AP-0008.

5 THE FLEX HYBRID STAGE
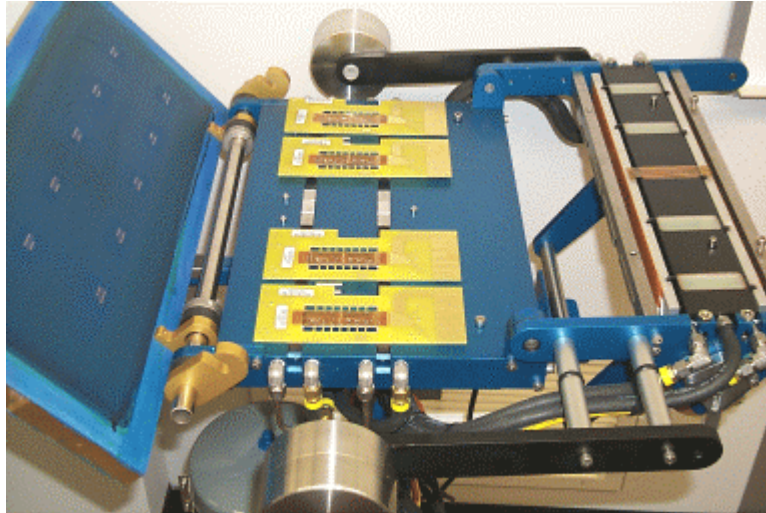
5.1 Assembly

Figure 12: Custom built laminator for attaching flex circuits to the frame PCB.

A custom tool (laminator) is used for attaching the bare flex circuits to the frame PCB (Figure 12). Up to five flex can be laminated in one load. The flex circuits are held in place by vacuum (right side of figure) while the frame PCB's are held in alignment by pins (centre of figure). An integral silk screen is used to apply a controlled amount of Loctite ChipBond 3614 adhesive to the frame PCB. The arm holding the flex is then rotated so that the flex are aligned over the frame PCB's and heated bars are pressed onto the flex tails to quickly cure the adhesive. This process takes about 5 minutes per load and achieves a placement accuracy of better than 300μm.

The surface mount components are loaded by automated pick and place machinery in industry Loading, reflow soldering and cleaning are quick processes. Visual inspection/repair takes somewhat longer. In all however, enough flex for a three hit system could be loaded in a matter of days if all the flex were delivered at once. Therefore, it is advisable to have on site supervision of the assembly process to reduce the risk of undetected systematic problems.

5.2 Testing

The flex hybrids are to be electrically tested for shorts and opens in industry, and only good flex shipped for production. However, the fast testing procedures used leave some possibility for failures up to the 5% level. As a quality control check, we plan to perform a more comprehensive test on at least 5% of the bare flex hybrids received, before they are loaded with components. These tests have been implemented at utilizing an automated probe station, Computer Aided Probe (CAP) , manual probes, a probe card and a frame PCB edge connector connected to an electronic switching system and an ohmmeter. The setup operates under control of a Labview program to automate the testing as much as possible. 90% of the electrical testing can be accomplished with the probe card and edge connector. The

other traces are tested using the CAP and manual probes. Using this system, one can perform a complete electrical test on a bare flex circuit in about one hour

Visual inspection will be performed on all flex hybrids after component loading and ultrasonic cleaning. By visual inspection, we seek to identify processing errors such as gross misalignment between the top and bottom metal, cover layer misalignment, cover layer or substrate defects and solder on the bonding pads. We also make and record physical measurements of the substrate and cover layer thickness, diagonals, trace width, bond pad width and the metal thickness.

The high voltage test is performed to insure that the bottom cover layer of each flex hybrid can hold off at least a minimum DC voltage (currently defined as 800 V). 95% of the bottom traces can be accessed through the frame PCB edge connector after the test wire bonds have been made. This is done by connecting all the edge connector leads to the test supply ground. The test supply high side is mechanically connected to a pad on the frame PCB which provides connection to the PCB under the flex circuit. The remaining bottom traces are 29 of the 32 LVDS FE output lines for each FE. These are tested on an automated probe station in combination with a CAP. Again, power supply ground is connected to the probe while the high side remains connected to the frame PCB under the flex hybrid. With the addition of a manual probe, the HV traces within the HV guard ring can be tested to the same value with respect to the guard ring. In this case, the test voltage is applied between the probe in contact with AGnd and the trace under test within the HV guard ring.

A Kiethly 2614 power supply is used, with current limit set to 300 nA when testing at the edge connector and 100 nA when testing other features. The voltage is incremented by 100 V steps to the final HV test value. If the current remains below the set limit after a short time for settling, then the HV test is passed. Measurement of the final maximum current is recorded in the database, except when a failure occurs, in which case the voltage at failure is recorded.

The surface mount component height must not exceed the mechanical envelope driven by detector assembly. To ensure this we perform an envelope inspection. Because the MCC and its wire bonds are near the edge of the envelope, we would ideally perform the inspection after the MCC wire bonds are potted. The envelope is inspected by use of an optical comparator to make a "GO"/"NO GO" decision on each component based on observed clearance under appropriate magnification (Figure 13).
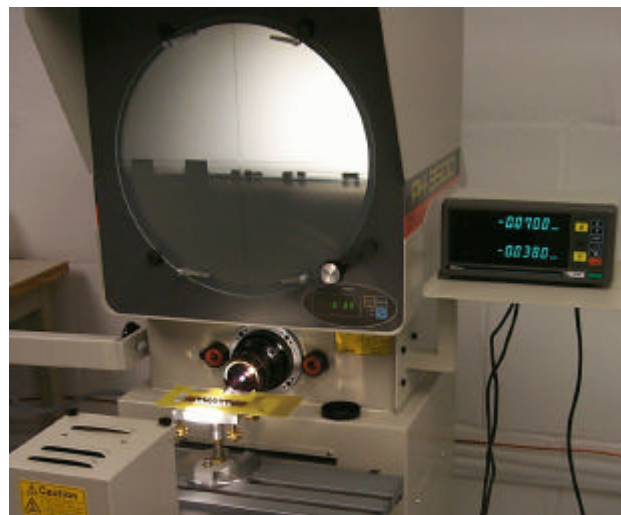

Figure 13: Profile view of the flex hybrid surface, viewed edge on using a 14" optical comparator.

6 PIGTAIL OR TYPE 0 CABLE ATTACHMENT

6.1 Barrel

To glue the barrel pigtail to the FLEX a solid adhesive film has been chosen to have maximum control of the glue shape and coverage and to avoid creeping of glue onto the bond pads. Equipment required includes a heater, tooling to align and press the Pigtail onto the Flex during curing of the adhesive and a microscope for alignment. With specialized equipment capabpe to controlled local heat and pressure (a flip chip bonder), it is possible to add the pigtail to the flex after the MCC chip. Without this equipment it is only safe to add the pigtail before the MCC.
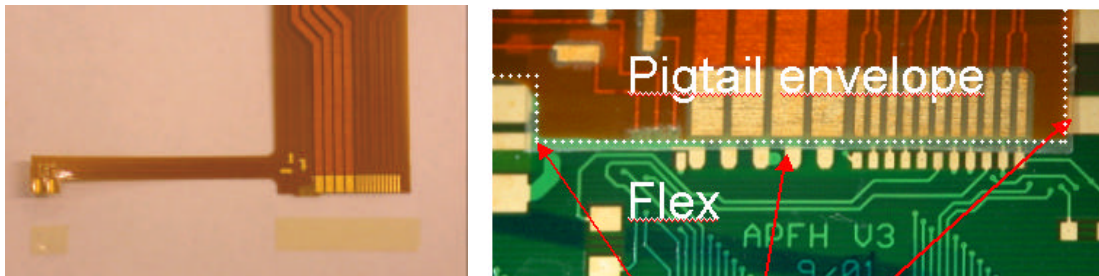

Figure 14: Barrel pigtail and Pyralux ribbons (left). Pigtail envelope next to bonding pads on flex hybrid (right).
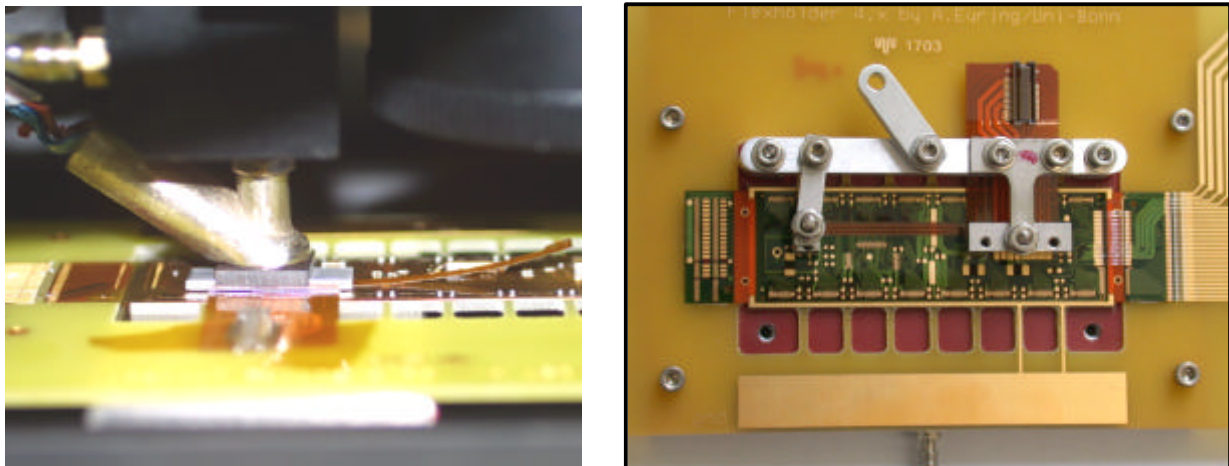

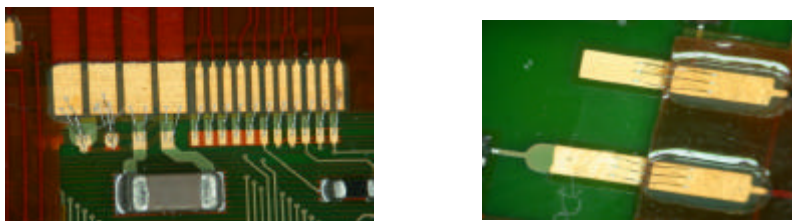Figure 15: Barrel pigtail alignment and gluing fixtures. Flip chip bonder (left) and simple fixture (right).

Figure 16: Barrel pigtail to flex wirebonds. All bonds (left) and detail of power bonds (right).

The glue film is cut into ribbons 17,0 x 4,5 mm^2 and 4,0 x 5,0mm^2 (Figure 14). The pigtail is then coarsely placed on the FLEX. By using a pin guided bridge assembly the pigtail is lightly held in position to allow precise alignment under the microscope. After the alignment the glue ribbons are placed between pigtail and FLEX. Five spring equipped screws (Figure 15) are tightend in order to firmly press the pigtail and the flat to the FLEX. Each of the 4 bolts apply a force of approx. 250cN. Finally the entire assembly is heated to 185°C for 60min.

The pigtail is then wire bonded to the FLEX. The wire bonds are made of 50µm pure Al wires. The four power pads are bonded with three wires and the signal pads with one wire. The HV bonds at the extension are bonded with three 17,5 µm AlSi wires (Figure 16).

6.2   Disks

The disk type 0 wires are soldered directly to the flex hybrid pads. A chlorine free, ultra-low residue no-clean solder is used. The power leads are soldered to the same pads used by the barrel pigtail (these provide the lowest impedance connection), while the signal and voltage sense wires are soldered to the test pads at the end of the flex hybrid, which are more convenient for the disk geometry. The high voltage wires are tacked to the surface of the flex hybrid past the MCC chip and soldered to the bias pads.

A silicone sleeve holds all the wires in a bundle. This sleeve is tacked to the end of the flex hybrid with a drop of glue. A disk module with type 0 cable is shown in Figure 2.
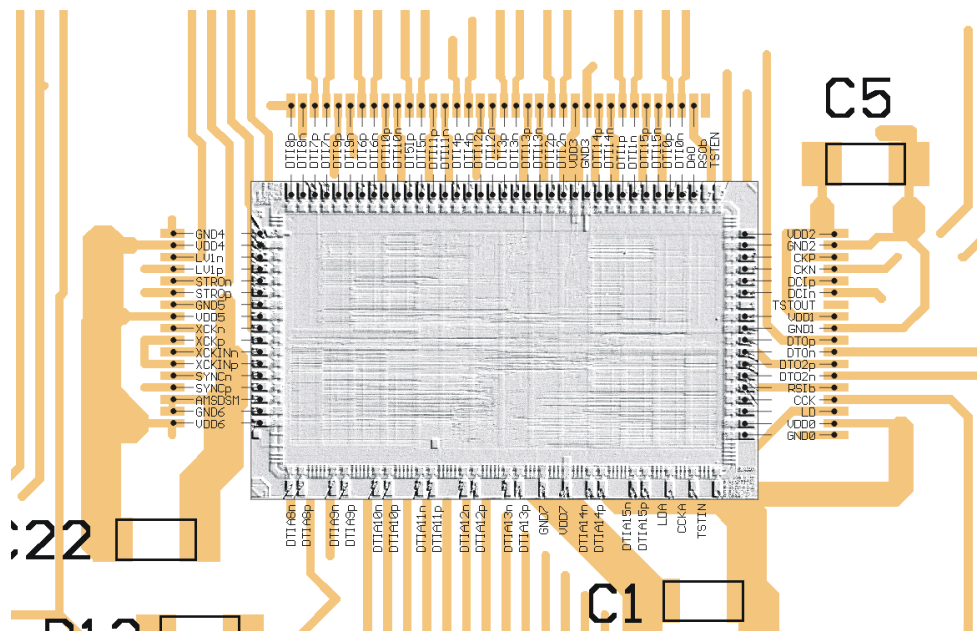
7   THE MCC STAGE

Figure 17: MCC on flex hybrid bonding diagram.

Before gluing the MCC on the flex hybrid, the flex hybrid bonding pads are cleaned with a plasma cleaner. The procedure to glue the MCC on the Flex is the following: a few tiny dots of glue are deposited on the Flex Hybrid, then the chip is placed on top of the glue and aligned with respect to the bonding pads under microscope. A small weight is applied on the MCC during polymerisation.

As with other adhesives, also this glue needs to be radiation hard. Since the heat produced by the chip is low (~100mA at 2V, 40 MHz clock), we do not have any strict constraints on the adhesive thermal conductivity and curing temperature. Good glue candidates used by the collaboration are a slow curing araldite, the Dow Corning SE4445 silicon and the Epotek 70.

The MCC is wire bonded to the flex using 25 µm Al(99%)-Si(1%) wires. The MCC bonding diagram is shown in Figure 17.

The electrical test of the Flex with the MCC consists of a set of parametric measurements and a functional test of the MCC itself. The combination of the two tests should provide a sufficiently precise indication, in case of test failure, of the location of the fault (i.e. detached wire bonds, broken lines, etc.).
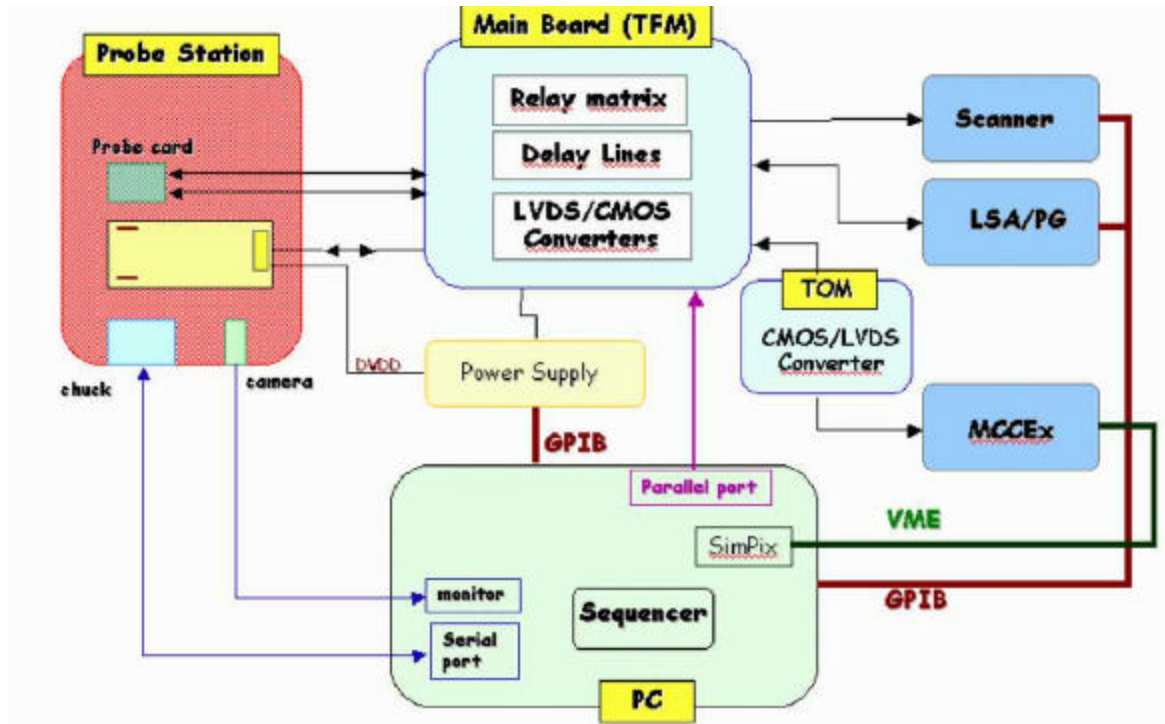

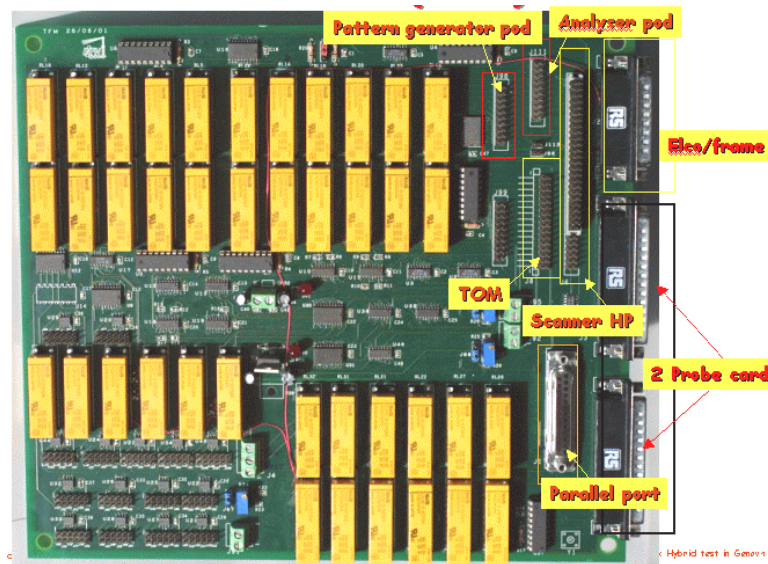Figure 18: MCC test setup diagram.

Figure 19: TFM board.

The test is performed in two steps:

- Connect the Frame PCB, holding the flex hybrid plus the MCC, to the flex test setup and perform parametric and functional tests like: MCC power consumption with and without clock, R/O of FIFOs and registers, event building with simulated events, parametric measurements on the MCC I/Os (VOH, VOL, RIN, etc.)

- Contact, in sequence using a probecard, each group of flex hybrid pads, that will be wire bonded to the FE chips once the module will be assembled, and perform additional parametric and functional measurements on the MCC chip.

The test setup is illustrated in the block diagram of Figure 18. and consists of following components:

- A main board (Test Flex Module, TFM) which is mainly a relays matrix to switch between parametric test (with power on/off) and the functional test (Figure 19: TFM board.);

- A power supply to provide DVDD (and check consumption) and supplies to the TFM;

- A programmable scanner connected to a DMM to perform Ω/V measurements;

- A Pattern Generator or the MCCExe to generate the input signals to the MCC (CK and DCI on the frame connector and DTI<i> on the probe card).

- A Logic State Analyser or the MCCExe to read and compare the MCC outputs: DTO/DTO2 from the frame connector and DI, LD, CCK, XCK, STR, LV1, SYNC from the probe card.

To contact the flex hybrid wire bond pads, we use an Alessi Probe Station. Its chuck has been modified to be compatible with the flex support frame. Attention has been put in the design of the chuck to make simple and safe the insertion and removal of the frame support card, to reduce to the minimum the risk of damaging. The chuck has a system of vacuum holder to maintain the Flex Hybrid perfectly flat to in order to have a good and precise contact of the needles of the probe card.

The probe card (Figure 20) uses two sides PCB and it has two facing rows of 30 needles each. The distance between the two rows is 22 mm which is slightly bigger than the distance of the pads on the flex hybrid. In this way we contact only one FE at the time, but we avoid the rotation of the flex during the test (when one FE is contacted the other row is a parking position).

The (estimated) time to test a flex is of a few minutes and is strongly dominated by the time needed to put the frame on the chuck and connect cables.
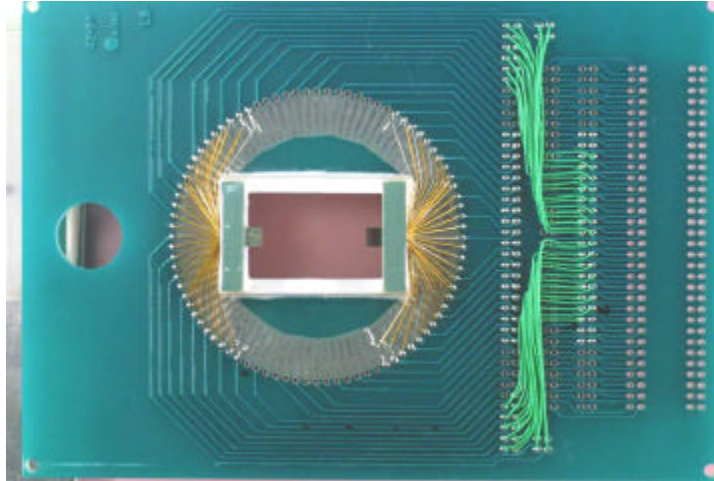

Figure 20: 2-Sided probe card for MCC on flex test.

8 THE FULL MODULE STAGE

The addition of a bare module to a flex hybrid (in its PCB frame) with MCC and pigtail or type 0 cable requires a gluing operation, described in section 10, and wire bonding of the FE chips of the bare module to the flex hybrid. This results in a full module in a PCB frame.

The full module in frame can be completely exercised electrically. In fact, this is the most versatile and complete stage of the module from a functional perspective. Once the module is integrated in the full detector some functionality will be lost. In particular external charge injection is only possible

in this stage, and dual link readout is only preserved in the detector for the B-layer. It is at this stage that the module will be extensively tested to obtain a complete characterization of the module properties. Functional details cannot be accurately predicted from test results of individual components before assembly. The characterization process is described in ATL-IP-QA-0015 and references therein.

9   ELECTRICAL CONNECTIONS

Electrical connections are made by soldering (for the surface mount components on the flex hybrid, the disk type 0 cable, and the barrel type 0 pigtail connector) and ultrasonic wedge bonding of aluminium wire. 25μm diameter wire is used for all except barrel pigtail to hybrid bonds, where 50μm wire is used. The hybrid to FE chip wire bonds must be low profile to fit between adjacent staves in the turbine geometry of the barrel detector. The same bond shape is used for disk modules even though no such constraint exists for the disks.

There are no special reliability concerns for soldered joints. 90% of wire bonds are single point failures for either a single chip or a module and therefore high reliability is a must. An effort is made to guard against 3 potential reliability issues: (1) placement of weak bonds, (2) mechaical damage of current-carrying bonds due to resonant vibration in the magnetic field, and (3) long term corrosion of strong bonds if there is chlorine ion contamination at the bond interface to the flex hybrid. The latter consists of thin gold (~10μin) over thick nickel plating (~100μin) of copper, as appropriate for aluminium wedge bonding and also soldering of surface mount components. The main quality control tool at our disposal is destructive pull tests of representative wire bond samples.

The module assembly procedure is designed to make sacrificial wire bonds at every bonding operation to be destroyed by pulling. During production the pull test results will be recorded in the database. Such rigorous approach has not been enforced in prototyping. The places for sacrificial bonds are (1) the ends of he flex hybrid that are glued to the frame and will eventually be cut away, and (2) the un-used bias grid bond for 14 of the FE chips (these are bonded to a floating metal pad on the flex hybrid). As far as evaluating log term reliability due to potential corrosion, not all wire bonds on the sacrificial ends of the flex hybrids will be pulled when they are made. Some are to remain there until after the module is removed from the frame and mounted on a local support. The empty frame can then be subjected to accelerated aging by heating, and the bonds can be pulled after that.

The minimum acceptable pull force for all destructive tests is to be taken from Military Standard 883, which essentially translates to 5g at the bond centre for 25μm wire. Pull test results from ~1000 bonds on mechanical prototypes with an early version of the flex hybrid are shown in Figure 21. The modules in the figure are shown in chronological order. Note that results improved with time as the bonding process was tuned. A non-destructive pull method has also been developed where an air jet is blown on the FE chip bonds. This should cause excessively weak bonds to break, but does not produce any data.

The potential for resonant vibration is eliminated by encapsulation. However, a special encapsulation technique must be used where only part of the bond is covered, because the hybrid to FE bonds span a gap between two mechanically separate structures (flex and bare module) with non-negligible relative motion due to CTE mismatch.
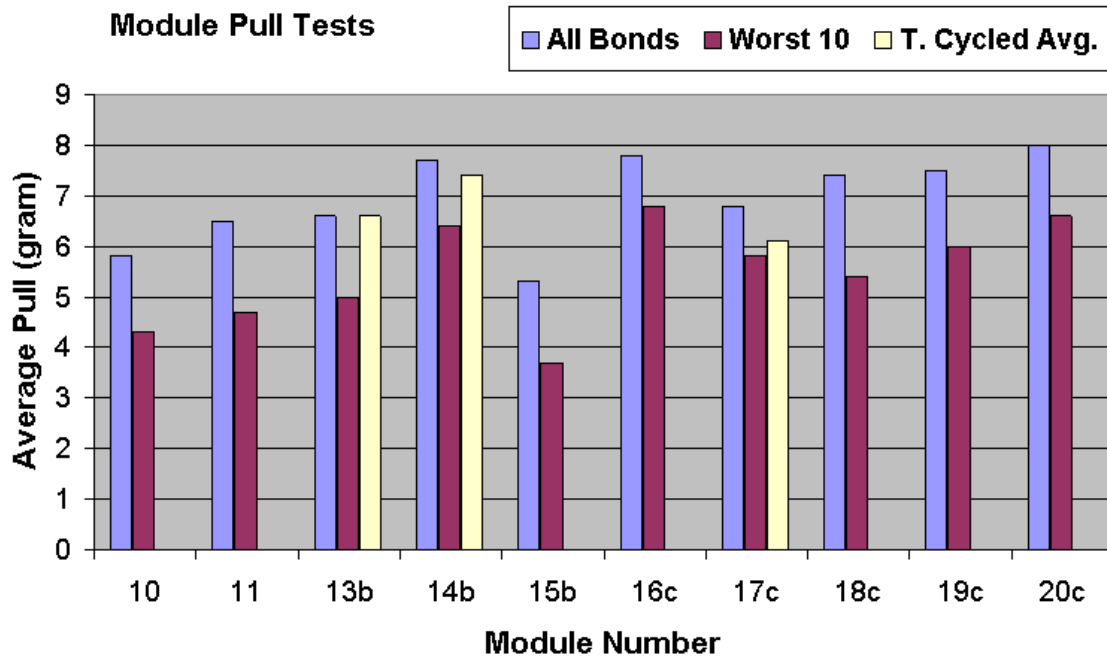
Figure 21: Destructive bond pull tests on mechanical prototype modules.

10 MECHANICAL CONNECTIONS

The bare module has two main glue interfaces: the module-support (MS) adhesive to connect the module to the local support and the flex-module (FM) adhesive to attach the Flex Hybrid circuit to the module. Unavoidable cool down stresses on module are due to CTE mismatch between different materials across the bonded interfaces. As stresses are proportional to the adhesive induced coupling, the glue interfaces must be compliant. Low shear strength glues and special glue deposition patterns are used to achieve this.

10.1 Flex Hybrid to Bare Module Glue

The Flex Hybrid loaded with the MCC and tested is to be glued to the bare module, on the sensor side. The adhesive interface between the Flex and the sensor must not be electrically conductive, must be radiation hard and must cure at room temperature, to avoid stress on the bumps. Moreover this interface, which also needs a deposition according to a predefined pattern, must fit other requirements:

- It must keep the Flex attached to the sensor (when the module is going to be attached on the local support, it is separated from the support frame and handled by the flex surface);

- It must stand the mechanical stresses coming from the pigtail (even if they are low, they will continue for years);

- It must have very low shear strength to minimise the mechanical stresses on the structures (in particular on the bumps) due to CTE mismatch;

- It must make the wire bond of the FE chips feasible, i.e. it must make a uniform rigid substrate under the flex wire bond pads.

Several silicone adhesives have been found that meet all the requirements. Two have been selected for the initial phase of production. They are both silicones with similar cured properties, but one is a pressure-

sensitive film, while the other is a liquid. The pressure sensitive film allows for fool-proof control the glue thickness under the wire bond pads as well as instant assembly (no cure time), while the liquid adhesive has been in use for a longer period of time and so there is more experience with it. Both adhesives will be used at least initially in production, in order to provide some safety margin against unexpected effects on modules loaded on local supports, where the prototype experience is quite limited. The geometry of the glue joint between flex and bare module is the same in both cases, and is shown in figure 22.
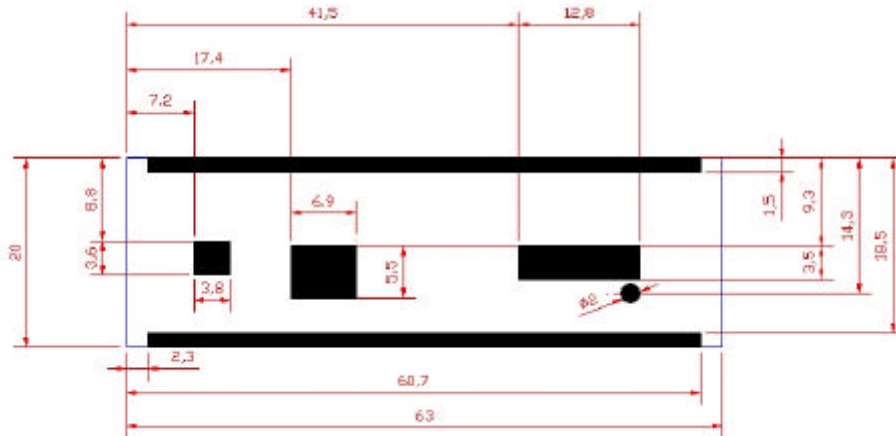

Figure 22: Flex hybrid to bare module attachment glue pattern.

10.2   Module to Local Support Glue

Modules are attached chip-side down to the local supports – barrel staves or disk sectors - using a thermal compound. The Module-Support (MS) adhesive must meet the following requirements:

- Radiation tolerant up to 50 Mrad.
- Strong enough to keep the module in the required position on the support.
- Low shear strength to reduce stresses. Thermally conductive to provide reliable heat transfer from the module to the support that is also the cooling structure.
- Must lend itself to reproducible application
- Must allow for module removal without any permanent damage to the support surface or to the neighboring modules.

A test program was pursued to find candidates that fulfill all requirements. Starting from 15 adhesives, the selection has found two good glue candidates: Eccobond45 and Dow Corning SE4445. The later adhesive, which is a 2-component silicone, was selected as the final production adhesive primarily due to a longer work time, that helps achieve uniform application, and slightly better removability.

Tables 2 and 3 show measurement results for critical mechanical and thermal performance. Results for Eccobond are included for reference.

Shear modulus (N/mm^2)	Before irradiation	After irradiation
ECCOBOND	0.7	7.5
SE4445	0.06-0.15	0.9-1.9

Table 1: Shear modulus test results

	Vendor specification (W/mK)	*results [W/mK]*	*results after irradiation [W/mK]*	*results after aging [W/mK]*	*test on stave: DT between Si and cooling*
ECCOBOND	*0.38*	*0.22*	*No change*	*No change*	*22.3C*
SE4445	*1.26*	*0.5*	*No change*	*No change*	*18.3C*

Table 2: Adhesive thermal conductivity results.

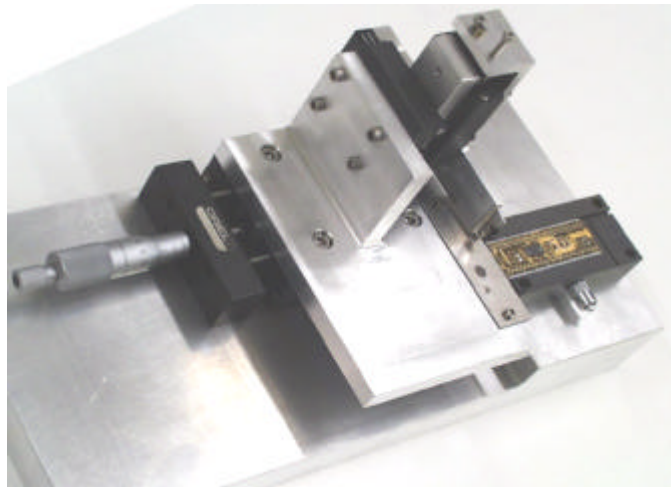# 11   MOUNTING ON LOCAL SUPPORTS

11.1   Removal from Frame

Figure 23: Flex edge trimming tool.

A module is finally removed from the PCB frame just prior to loading on a local support (sector or stave. Removal involves simply cutting the flex hybrid at both ends, separating the body of the hybrid from the sacrificial ends that are glued to the PCB frame. There is no metal on the flex in the areas to be cut and there is very wide clearance (5mm) to make each cut.

There is one complication in the case of barrel modules, which is that the flex cannot protrude beyond the sensor edge by more than 100 µm, as specified in ATL-IP-EP-0024. Thus, after cutting out of the frame, the flex must be trimmed to meet this constraint (this is not necessary for disk modules). A special tool has been built for this operation, and it has been shown to work with good repeatability. A photo of this tool with a mechanical prototype module is shown in Figure 23.

11.2 Pickup and placement on staves

This section describes the module mounting on the barrel local supports (Staves). The requirements for this operation are given in a separate document: ATL-IP-EP-0024, which is the official source of this information. Requirements given here are for reference only.

The module placement on barrel local supports will be done in multiple sites. Tools have been prototyped and tested to reach a high degree of safety and accuracy for the module placement. The nominal module placement procedure concerns the glue deposition, the stave metrology and the sequential module assembly on stave. The tools were also designed to permit the replacement of a broken module on a fully equipped stave.
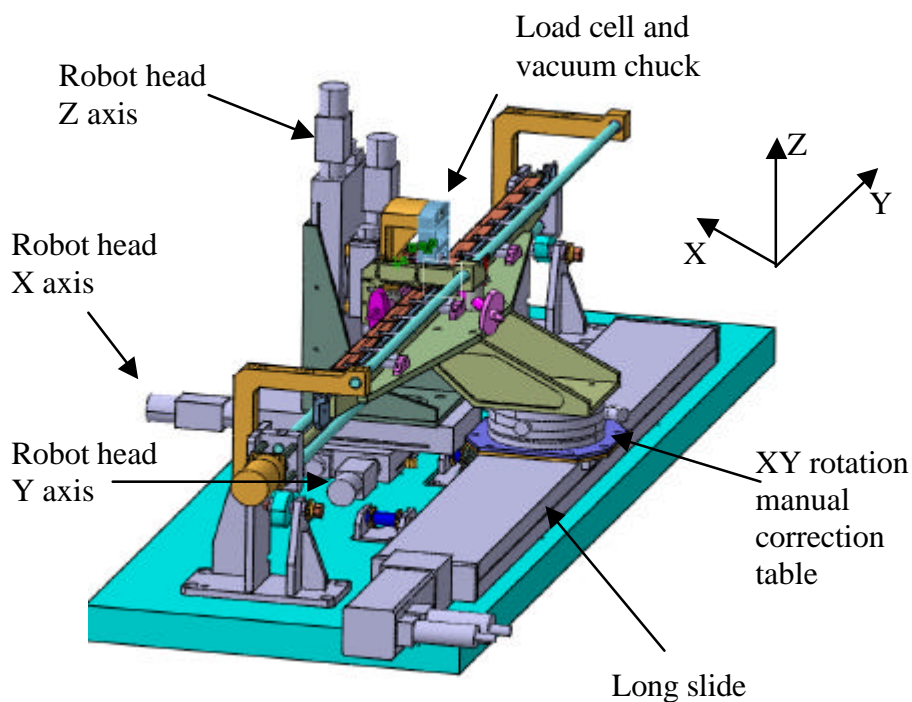

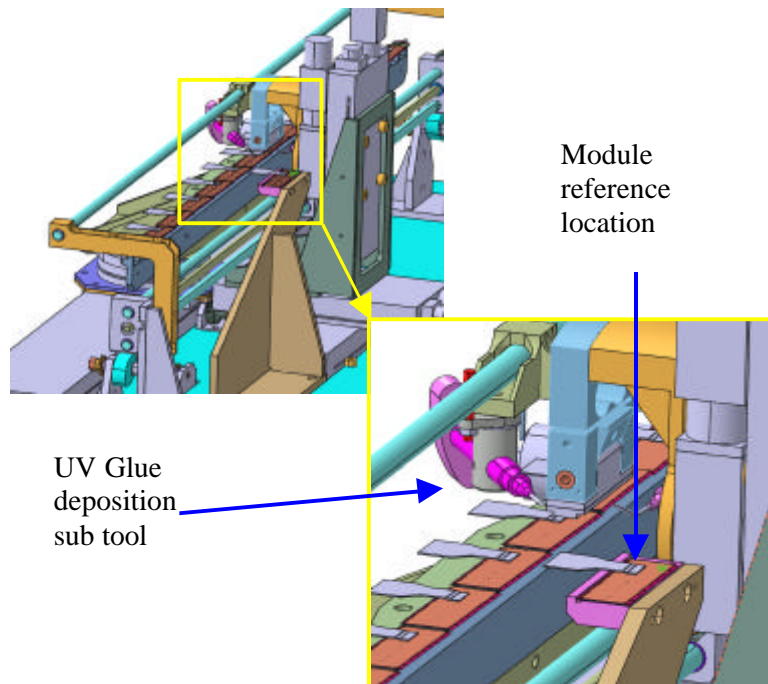Figure 24: Module on stave loading tool (5 DEOF)

Figure 25: The stave geometrical reference defining procedure. Detail shows the module reference location and the UV tack application.

Module placement is done with a robot. The first task before module loading is to assemble the stave on a cradle with 5 supports points, which is the interface with the robot. The cradle allows safe handling of the stave after module loading. It is used also for:

Testing modules after loading on stave

Cable connections to module pigtails

Safe connection for cooling
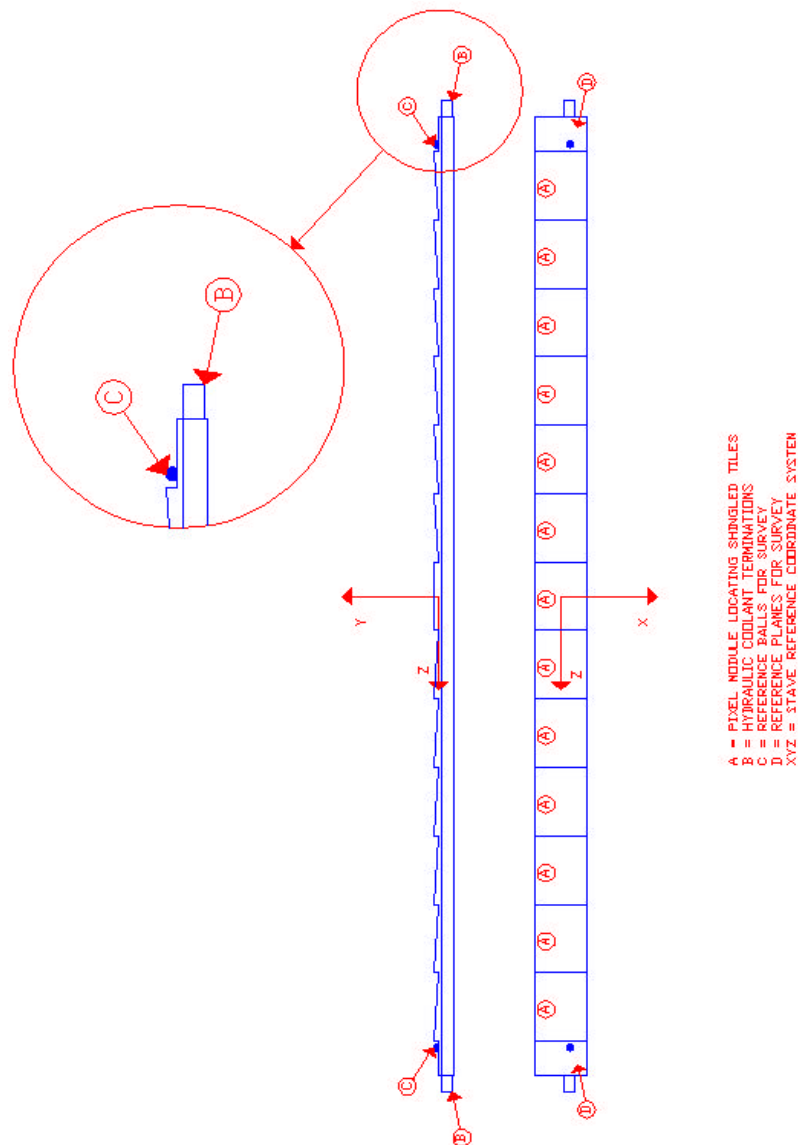
Stave storage before bi-stave assembly

Figure 26: Stave geometrical reference. Taken from ATL-IP-EP-0024 and included here for reference only.
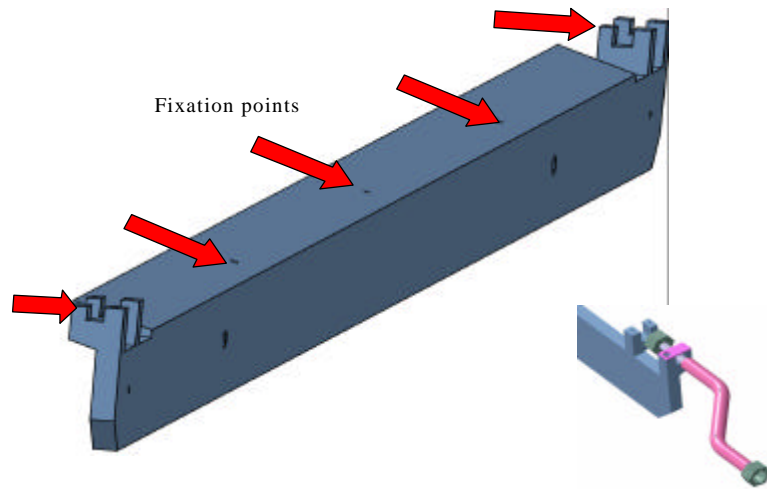
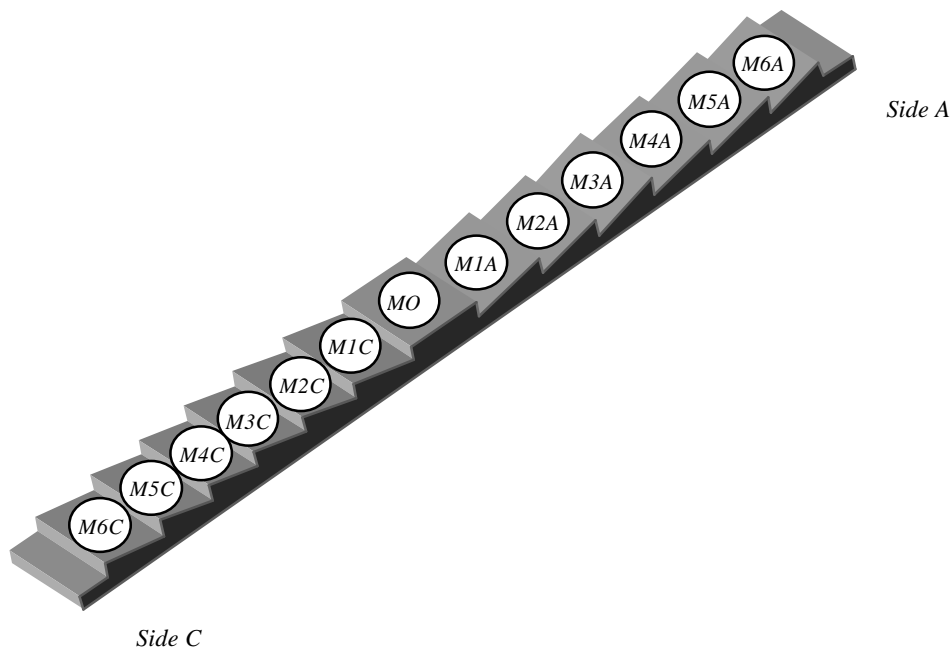Figure 27: Stave cradle and cooling connection compliant system

Figure 28: Stave loading numbering reference

The assembly sequence with reference to Figure 28 is as follows:

Sequential module assembly on the sites M6C,M5C,M4C,M3C,M2C,M1C

Sequential module assembly on the sites M6A,M5A,M4A,M3A,M2A,M1A

Final assembly of the last module on site M0

The assembly of each module proceeds as follows. The module is first placed on the robot. The module is placed manually with a vacuum chuck pencil on the reference location. This action requires to

slightly push it in plane in the X direction against one pin in the Y direction. When the module is in place, it is secured with vacuum.

The tilt angle and Z stave location (site) are now tracked with the robot. A specific procedure is foreseen to trace the Z location and Tilt angle with the robot, before the glue and module deposition. This task is made by using the robot rotation table and its Z axis stage. When the location is found the robot stops 0.1 mm above the surface and the module deposition location is registered. An additional safety task compares the stave measurements made with the robot to probing data. The tilt angle is registered, and will be used for the glue dispenser displacement parallel to the surface.

The glue deposition can now take place. The glue deposition requires the maximal glue contact surface without glue in the inter-chip region (Figure 29). A cross deposition pattern was tested successfully at Marseille, while a point deposition procedure was also successfully tested at Wuppertal.

Figure 29: Glue between glass slide and carbon support showing required end result.

Many parameters must be tuned in order to get the most efficient deposition:

Robot head speed

Distance between the needle and the C-C surface

Pressure inside the dispenser

Diameter of the needle

Age of the glue mixing

The cross deposition procedure, shown in Figure 30, has been selected for production.

Needle directly handled by the robot head
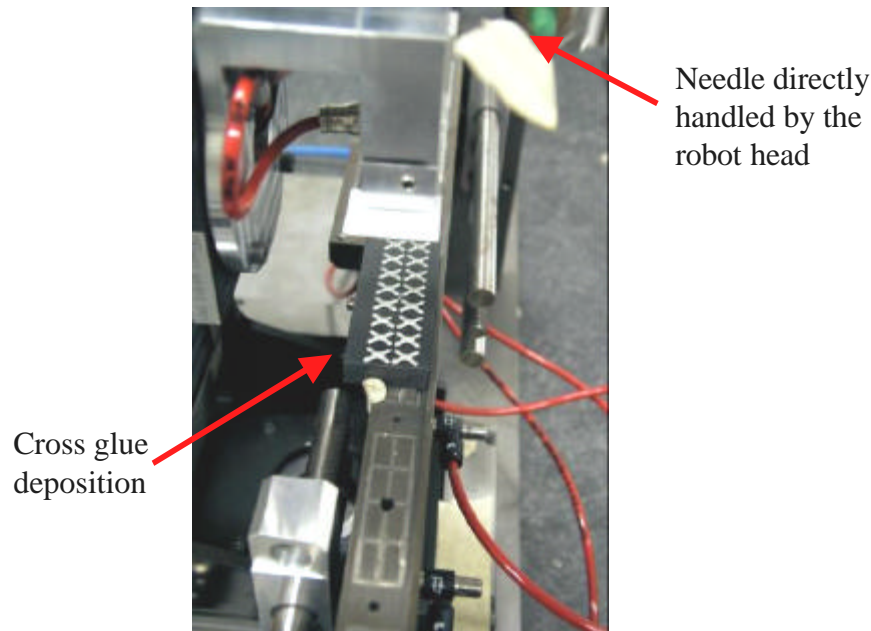
Cross glue deposition

Figure 30: Cross deposition glue pattern on a part in robot.

The module placement proceeds as follows:

The robot head goes to pick up the module on the reference position

The load cell is checked during the motion to avoid any contact with the module

The reference position vacuum is switched off

The robot head vacuum is switched on

We check the value of the load cell to detect that the module is properly handled, and a pressure sensor which is on the vacuum line to check its quality

The robot moves the module to a position vertically above the placement area.

We can check and correct eventually the module position if required

The module is laid on the stave gradually by controlling the force applied on it (the actual force threshold is 100g, any overload will stop the motion unit the force decreases)

The loads and the Z displacement versus time are recorded in order to trace the placement.

When the final location is reached the module reference marks are measured.

The plan is not to use UV tacks to hold the module in place during glue cure but rather to let the glue before releasing the module from the chuck and depositing the next module. This is a conservative choice to avoid risk from potential long term effect of stress from the UV tacks, which can only be seen with high statistics and long time, and therefore cannot be demonstrated not to exist.

11.3   Module Replacement

An important capability of the tooling is to permit replacing a module after a stave has been loaded. This may be necessary if electrical testing reveals a problem once a module is loaded on a stave. The module replacement procedure consists of module removal followed by module placement. Module removal is a manual operation which proceeds as follows:

Warm to 80°C the bad module with a hot air blower (tool traditionally used for de-soldering). The module temperature is monitored by gluing a thermal sensor on it

When the module is hot, a thin wire of tungsten (50 microns) is slid between the local support and the module to slightly break the glue layer.

The bad module is lifted from its position

After module is removed the stave surface is cleaned by peeling the remaining glue and by wiping with acetone.

The module replacement after removal is similar than the placement procedure in the standard case. The main difference is in the last step to press the module on the glue and locate it. This is no longer a pure translation motion but a combined rotation and translation to slide below the adjacent module, which is normally not yet there in the standard placement (see Figure 31).
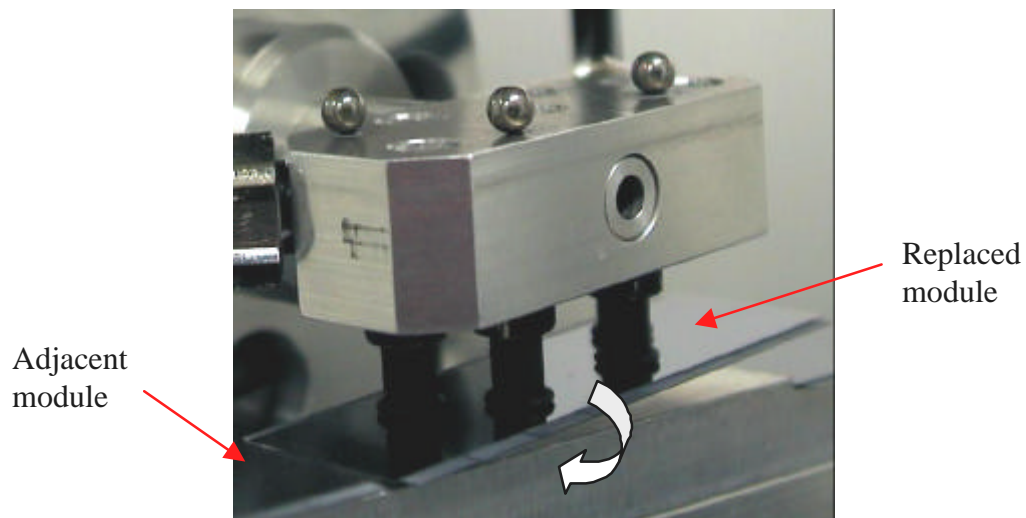

Figure 31: Module replacement

11.4   Assembly Accuracy Requirements

The assembly accuracy requirements as given in ATL-IP-EP-0024 are: ± 50 microns in X, ± 50 microns in Y, and +50 microns and -25 microns in Z direction. Figure 32 shows the XY accuracy reached with the actual tool on half of a stave.
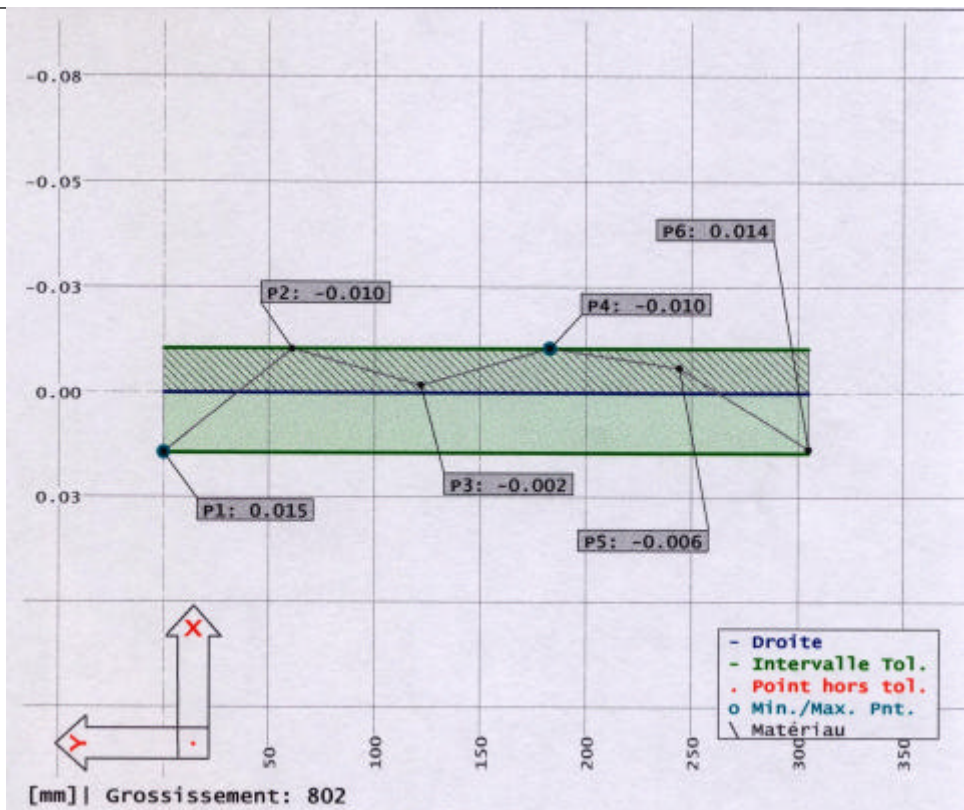
Figure 32: Measured location accuracy of modules placed on prototype stave.

11.5   Placement on Sectors

Loading modules onto a sector is conceptually similar to loading on staves, but the sector geometry greatly simplifies the operation, and the number of modules to be loaded is much smaller. For these reasons a robotic method has not been developed for the disks. The tooling is built about a smart scope coordinate measurement machine, where a program locates the sector references an points the user to the location each module should have. A vacuum chuck registered on guide pins holds the module close to this location, and then the operator must make fine manual adjustments to move the module to the exact predefined location. A placement repeatability of +/- 10μm in X-Y is achieved with this method. A photograph of the disk module deposition setup is shown in figure 36.

After a final glue has been selected for stave loading the same will be used for sectors. The same accuracy requirements are used as for stave assembly (from ATL-IP-EP-0024).

The sector loading tool is manual rather than a robot. To load a module it is first picked up with a vacuum chuck similar to the stave pickup chuck and aligned above the placement position without any glue present. The sector itself can be held in the tool base in 3 different positions, one for each module location. To align a module for each position the operator adjusts the X,Y location of the module in the tool using differential screws. After alignment the tool is opened, removing the module from just above the sector, the glue is applied, the tool is closed putting the module into place, and contact pressure is applied during glue cure. Photos of the sector loading tool are shown in Figure 33 and Figure 34.

Control of the glue gap between module and sector follows a different approach than the barrel. Since the module is set down by hand, there is not way to accurately control the height between the module and the sector surface. Therefore, a mechanical stop is used to define the gap between sector and module. The stop is made by stretching 75mm monofilaments on the sector surface. These remain in place after assembly is complete. They can bee seen in Figure 37.
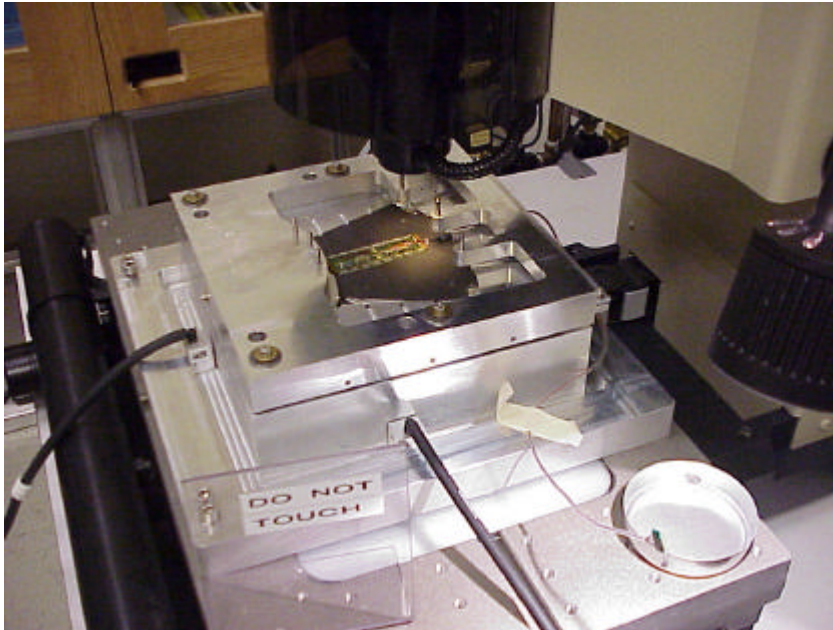
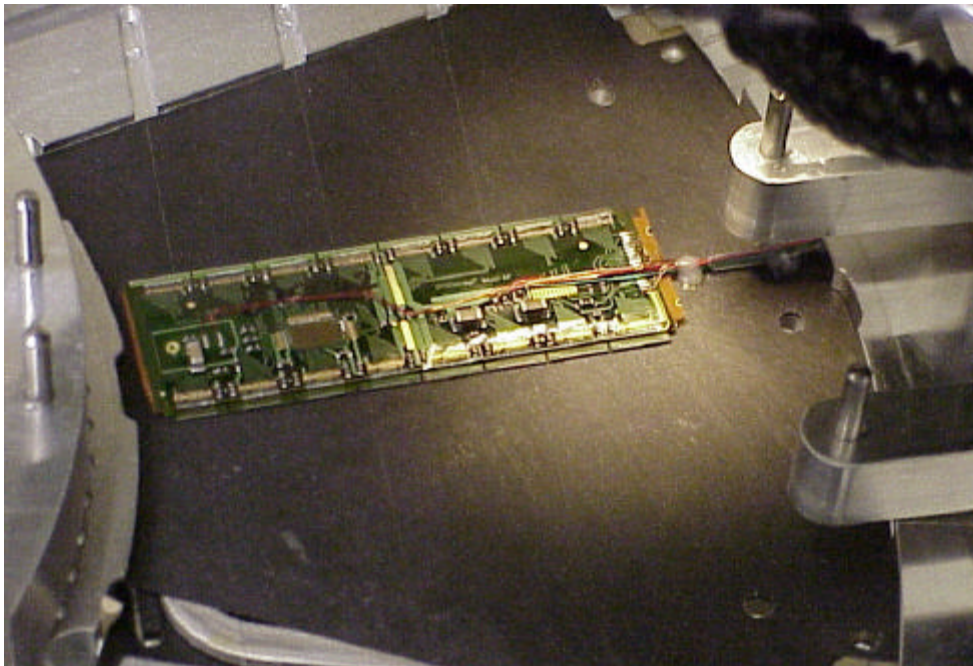Figure 33: Tool for loading module on sector in smart scope coordinate measurement machine.

Figure 34: Close-up view of prototype module loaded on sector. Three monofilaments between modujle and sector face are just visible.

12 PRODUCTION DATABASE

The Pixel production data, including module and its components information, are being stored in the Oracle 8i database (PDB). All the components have ATLAS unique serial numbers[1] as the PDB primary keys. The data structure used in the PDB corresponds to the Pixel detector mechanical assembly structure. The table in Figure 35 represents an example of module prototype (ATLAS serial number 20210021410064) assembly, composed of bare module and flex hybrid with MCC mounted, with links to more detailed information about components and tests.

Module number	Module type	Test list	Item number	Sub-assembly	Creator	Assm Date
-						
20210021410064	ModuleFEIPrototype	Tests: Gen.info	20210210142303	BareFEIModuleProt	P_GEN	18-JUN-02
			20210010410064	FlexMCCPrototype	P_GEN	07-JUN-02

Figure 35: Example of module prototype in database.

The module item table (Figure 36) contains module information about the quality (passed: yes/no), location and user to which this module belongs, the current state (assembled: yes/no), manufacturer of most important module components, the name given by institute and the date of registration:

Serial number	Mfr Ser number	Item Type	Date	Mfr Bare	Mfr Flex	Mfr Tile	Passed	Location name	Assembled	Owner
-										
20210020410059	Bonn_Module_1	ModuleFEIPrototype	17-JUL-02	IZM	Compunetics	CIS	NO	University of Bonn	NO	P_BON
20210020420001	Bonn_Module_2	ModuleFEIPrototype	19-SEP-02	IZM	Dyconex	CIS	NO	University of Bonn	NO	P_BON
20210020420032	Bonn_Module_3	ModuleFEIPrototype	12-NOV-02	AMS	Dyconex	CIS	NO	University of Bonn	NO	P_BON
20210020420034	Bonn_Module4	ModuleFEIPrototype	12-NOV-02	AMS	Dyconex	CIS	NO	University of Bonn	NO	P_BON

Figure 36: Module item table.

The information is being uploaded via specific java application, which performs different crosschecks to reduce the probability of operator error.

To facilitate the part tracking the serial numbers carry some useful information about their origin. The last 6 digits of module serial number are derived from the serial number of flex hybrid, used in this module assembly[2].

The PDB report facility allows selections of parts and tests by different parameters like type, date, laboratory name, manufacturer name etc, which helps to keep the production process under control.

The PDB is being updated permanently with the shipment data as well. Relevant documents are:

---

[1] ATC-OQ-QA-2040, ATLAS Part Identification.

[2] ATL-IP-MN-0002, Part Numbering in the ATLAS Pixel Production Database,
 ATL-IP-AP-0008, Pixel Flex Hybrid and Module Bar-Code Tracking.